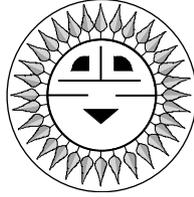


Overcurrent Devices



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In the *Code Corner* columns in *HP76–83*, I addressed the selection and sizing of conductors for renewable energy systems. How do we protect these conductors from long-duration overcurrents that might cause fires or shocks if allowed to continue? Overcurrent devices provide the required protection, and this *Code Corner* will be the first of several addressing these devices.

We have sized the conductors in our system to operate within the rated temperature of the wire insulation at some maximum current. If that current is exceeded for significant periods of time (depending on the magnitude of the overcurrent), the conductors and the insulation will be heated. As the conductor temperature passes the rated temperature of the insulation (60, 75, or 90°C; 140, 167, or 194°F), the properties of the insulation will change. The hotter the insulation gets above the rated temperature, the faster the insulation characteristics change, and the more they change.

Some insulation (thermoplastics like THHN) may soften, melt, and then smoke before catching fire. Others (thermoset plastics like RHW) may start to char and become brittle before catching fire. Operation above the rated temperature for any significant length of time will change the insulation properties that make the wire safe, and will reduce its life. These changes in the insulation may not be perceptible, but they may be hazardous.

Types of Overcurrents

Overcurrents can be grouped into categories. Starting surge currents from motors or electronic devices at two to ten times normal running current can last 1 to 8 seconds. Overloads are in the range of two to six times normal rated circuit current and can last from minutes to hours. Fault currents are unexpected and unwanted currents, at varying levels, that can occur on the normal

circuit conductors or on grounded conductors. They can be continuous (low levels) to very short-lived (high levels) in a well designed system.

Overloads are the result, as the name implies, of connecting too many loads to a given circuit, or connecting loads that draw more current than the circuit is rated to deliver. Most electrical circuits are designed to be operated at only 80 percent of their rating. While operating above this level may not cause the overcurrent device to trip, it may result in long-term degradation of the circuit wiring and overcurrent devices.

Overcurrents from faults can result from mechanical failures of insulation, failures of connections, or abuses of the wiring such as nail punctures, saw cuts, or general wear and tear. Fault currents are called line-to-line faults if the fault or short circuit involves both of the current-carrying conductors. If the fault involves a circuit conductor and a grounded conductor, an equipment-grounding conductor, or a grounded surface, the fault is said to be a ground fault.

Fault currents may be in the milliamp range when leakage currents or high-resistance faults are involved. Very high fault currents, up to the ability of the power source (which may be thousands to tens of thousands of amps) may occur when a direct, low-resistance, unwanted connection is made.

Overcurrent Devices

The main types of overcurrent protection devices used in renewable energy systems are fuses and circuit breakers. These devices have been around for over 100 years and have been steadily refined in that time. These devices are very sophisticated in their internal construction. They use electrical, mechanical, magnetic, thermal, and chemical processes to achieve the desired characteristics.

The characteristics that are required in an overcurrent device are stringent and difficult to achieve. Not all overcurrent devices meet all of the criteria for all applications. This is why there is a large selection of overcurrent devices, with a wide range of appearances and costs.

In general, all overcurrent devices are designed to open a circuit when subjected to overcurrent, and then reduce that current to zero. These devices have a specific opening current rating, also known as the ampere rating. They must also have a voltage rating and an interrupt current rating.

The voltage rating specifies the maximum voltage that the device can be subjected to, including device-to-ground voltage and the voltage across the device after

it has opened the circuit. The interrupt current rating is the amount of short-circuit current that the device can interrupt (reduce to zero) when opening. All overcurrent devices must be able to function properly and safely when subjected to any voltage up to the rated voltage and any current up to the interrupt current rating.

Strangely enough, short-circuit currents and voltages below the maximum values are far harder to handle than those near the maximums. High short-circuit currents tend to cause internal fuse elements to melt rapidly and completely, creating a long open circuit path that the current must jump. Lower short-circuit currents do not melt the fuse elements as completely, which leaves smaller gaps in the internal element. The currents jump across these smaller gaps more easily than the longer gaps, and the internal fuse mechanisms have more trouble extinguishing the arcs.

Circuit breakers have slightly different problems related to the strength of the magnetic fields that cause their internal contacts to open. Lower short-circuit currents cause the contacts to open more slowly, and the arc is harder to extinguish than when higher short-circuit currents force the contacts to open rapidly.

Each device, fuse, or circuit breaker is designed for its specific application. “Slow-blow” fuses or time-delay circuit breakers are designed to not respond to current surges, but only to longer duration overloads. “Fast-blow” fuses and short-delay circuit breakers are designed to respond very quickly to overcurrents above their rating, and may even open if subjected to normal starting surges from motors and electronic devices.

Both slow- and fast-acting overcurrent devices may be used for overcurrent protection in code-compliant systems. The specific application will determine which device should be used. In another category are “semiconductor” fuses, which are designed to respond extremely quickly to protect semiconductors inside electronic equipment. Unfortunately, this characteristic cannot be achieved while meeting the code and UL requirements to respond properly to overloads in the two to six times rating area. So these fuses are not approved for use in code-compliant systems.

AC & DC Are Not the Same

It is not safe to use an overcurrent device listed only for AC in a DC application. AC currents go to zero and reverse themselves 120 times per second (on 60 Hz systems). Any arc formed when an overcurrent device opens is extinguished and re-struck 120 times per second. This greatly assists the overcurrent device in interrupting the current and forcing it to zero. DC current does not provide this self-extinguishing effect, and since it flows in one direction only, the overcurrent device

must bear the complete load of breaking the circuit and extinguishing the arc.

The difficulty in interrupting DC currents is quite evident in the ratings of the common 100 amp type RK-5, DC-rated fuse. This fuse is listed for use on both AC and DC systems. The ampere rating is 100 amps AC and DC. The AC voltage rating is 250 volts. The DC voltage rating is only 125 volts. The fuse can interrupt AC short-circuit currents up to 200,000 amps. The DC interrupt rating is only 20,000 amps. Half the voltage and one-tenth the interrupt rating highlight some of the difficulties associated with DC circuit overcurrent protection.

Fuses

Fuses act once in protecting a circuit from overcurrents, and then they must be replaced. Special fuse holders must be used to allow safe replacement of the blown fuse. These protect the user from coming into contact with energized circuits. In many cases, the fuse holder is incorporated into a disconnect switch that removes voltage from the fuse when opened.

Listed fuses are available in two categories. “Class” type fuses are subject to more rigorous testing in terms of the interrupt rating, the number of cycles at full load, environmental conditions, mechanical design, and other factors.

“Supplementary” fuses, on the other hand, are designed to be used in circuits where the conditions of use are much less severe. They are usually protected from high short-circuit currents by class type fuses—hence the name supplementary; they supplement other overcurrent protective devices in the system.

Class type fuses are more robust, and can be used in all applications. When used in DC circuits, the fuse must also be listed for DC use. The RK-5 fuse mentioned above is a class type of fuse. Other fuses that may have DC ratings are class RK-1, CC, J, T, and L. These fuses are available with various ampere ratings, voltage ratings, and interrupt ratings. Class type fuses may have standard ampere ratings of 1, 3, 6, 10, 15, 20, 25, 30, 35, 40, 45, 60, 70, 80, 90, 100, 110, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, and higher, up to 6,000 amps.

“Supplementary” type fuses can be used only in DC PV source and output circuits. This type of fuse includes the midget fuse and one or two ceramic fuses in the 1/4 by 1-1/4 inch (6 mm x 32 mm) size. These fuses have limited interrupt capabilities (500 to 1,000 amps or so), and are allowed only in the PV source circuits that are some distance from the sources of high, short-circuit currents like the battery. Ratings are usually in one-amp increments from one to 30 amps.

Very few of these fuses are listed for DC. Care must be used when selecting these fuses or replacements to ensure that the replacement has a DC rating and listing. Fuses available at electronics hobby stores may look similar, but usually do not have the listing or DC ratings. Where possible, it is suggested that the more robust class type of fuse be used in all applications. Due to volume production, the class fuses are, in some cases, cheaper than the supplementary fuses.

Circuit Breakers

Circuit breakers can be reset after opening, and can be reset numerous times. They can also be used as disconnect switches. Replacement is not needed after every operation. Only the operating handle is exposed, and the energized contacts are not accessible to the system user during normal operation. Circuit breakers are known as inverse-time devices, and they have various time delay curves, just as slow-blow fuses do.

For example, a circuit breaker rated at 30 amps must carry 30 amps continually without tripping. It must open within one hour when carrying 135 percent of 30 amps (40.5 amps), and it must open in 2 minutes when subjected to 60 amps (200 percent of rating). Within these ranges, the circuit breaker may be designed for slow or fast response to short-term (1 to 2 seconds) and long-term (2 to 8 second) surges.

Circuit breakers are also available in two versions. The "branch-circuit-rated" circuit breaker is equivalent to the "class" type of fuse. There are also supplementary rated circuit breakers that could be used in PV source and output circuits, but these are not commonly available. In all cases, DC-rated and listed circuit breakers should be used in DC circuits.

Time Constants

When a short circuit occurs, the fault current does not rise instantaneously to the maximum value determined by the source voltage and the circuit resistance. There is a time constant involved that is determined by the resistance, inductance, and capacitance of the circuit. These in turn are controlled by the insulation type, conductor spacing, and length of each circuit.

Fuses and circuit breakers for DC systems are tested and listed to operate with time constants of 10 milliseconds or less. This time constant impacts overcurrent device performance in two ways. First we have the useful current-limiting fuses, and second we have the problems associated with time constants that are too long.

Current-Limiting Fuses

A normal fuse (non-current-limiting) will sense the short-circuit current as the current increases past the fuse ampere rating on the time-constant slope toward the

maximum value. These standard fuses will eventually open the circuit and extinguish the arc, provided that the maximum available short-circuit current is lower than the interrupting capability of the device. However, the current through the circuit may reach or nearly reach the maximum available short-circuit current for the circuit. These high levels of current may damage other components in the circuit.

Current-limiting fuses will also sense the rising current as it passes the ampere rating of the fuse. They will, however, act much faster than the non-current-limiting fuse to open the circuit and extinguish the arc. The action is so fast (substantially less than 10 milliseconds) that the current never has a chance to increase to the short-circuit maximum current. The short-circuit current is held to a much lower value that results in considerably less stress to circuit components. Current-limiting fuses are sometimes required on battery circuits where the available short-circuit currents can be very high. There are no current-limiting circuit breakers listed for use on DC systems.

Long Time Constants

DC overcurrent devices may not work properly if the circuit time constant is substantially longer than 10 milliseconds. The overcurrent device may have trouble extinguishing the arc. At voltages below the maximum rated voltages and at low short-circuit maximum currents, long time constants prove especially troublesome.

As the length of the circuit conductors increases, the resistance of the circuit increases. As the spacing between parallel circuit conductors (positive and negative) increases, the inductance of the circuit increases. Capacitance varies with spacing, but not in a uniform manner. These three factors (resistance— R , in ohms; inductance— L , in henries; and capacitance— C , in farads) serve to determine the time constant of the system.

The *NEC* requires that all conductors in a circuit, including the equipment-grounding conductor, be routed together and remain in close proximity. In DC circuits, this action keeps the time constant as low as possible. In AC circuits, impedance is minimized.

PV system designers and installers should keep this requirement in mind when working on module and battery wiring. All of the conductors for each circuit should be grouped together in the same conduit or sheathed cable to keep the time constants low.

Overcurrent Devices for Other Systems

Yes, there are many overcurrent devices (both fuses and breakers) that are used on other DC systems such as electronic, appliance, telecom, automotive, boat, and

mining systems. Most of these overcurrent devices have not been evaluated by the listing organizations against the UL standards and *NEC* requirements of fixed electrical power systems.

For example, automotive fuses and circuit breakers are designed (at very low cost) to be used in relatively high-resistance circuits (one conductor is the steel auto body; or small wires are used) that limit the available short-circuit currents to a low value. They do not have sufficient interrupting capability to deal with the much higher short-circuit currents found in fixed-power systems. When used in fixed-power systems, such as PV systems, they may create hazardous conditions when they are required to function.

Very expensive, high-reliability, overcurrent devices made for industrial and telecom systems may meet the technical requirements for use in a PV system. But they have not been evaluated or listed for use in RE systems that must meet *NEC* requirements.

Generally, the overcurrent devices available and listed for use on fixed electrical power systems are the lowest cost means of achieving the required protection. To use overcurrent devices that are not listed, or that are intended for other industries, may either sacrifice safety or increase cost.

Summary

Ungrounded conductors in all circuits are required to have overcurrent protection. The proper fuse or circuit breaker can provide this protection. DC ratings are required for overcurrent devices used in DC circuits. Keeping all of the conductors of a particular circuit in close proximity will keep the time constant low and allow the overcurrent devices to function properly. In future *Code Corner* columns, I will address where overcurrent devices should be used, and how to size and select the proper devices.

Photovoltaic Power Systems and the National Electrical Code: Suggested Practices

This 117 page manual, written by the *Code Corner* column author, and published by Sandia National Laboratories, has been revised to the 1999 *NEC*, and is available in PDF form on our Web site: www.nmsu.edu/~tdi/pvandnec.htm

This manual is also available from Sandia National Laboratories by calling Connie Brooks at 505-844-4383 or e-mailing her at cjbrook@sandia.gov.

Questions or Comments?

If you have questions about the *NEC* or the implementation of PV systems that follow the requirements of the *NEC*, feel free to call, fax, e-mail, or write me. Sandia National Laboratories sponsors my

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